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On the influence of car brake system parameters on particulate matter emissions

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ABSTRACT

The influence of car brake system parameters on particulate matter emissions was investigated using a pin-on-disc tribometer. Samples from a low-steel friction material and a cast iron disc were tested for different sliding velocities, nominal contact pressures and frictional powers. Disc temperatures were also measured. Their impact on total concentration, size distribution, particle coefficient and transition temperature was analysed. Results show that frictional power is the most significant brake system parameter. However, temperature, as a response parameter, is the most influential, inducing a shift towards the ultrafine particulate fraction and raising emissions. A transition temperature, independent of the system parameters, was identified.

1. Introduction

Among road-traffic related pollutants, brakes have been estimated to contribute 55% by weight to the total non-exhaust PM10 emissions fraction (i.e. airborne particles with an aerodynamic diameter of less than 10 µm). Furthermore, they account for 21% of overall road-traffic related PM10 emissions [1]. In addition, particulate matter (PM) induces adverse health effects [2,3] and contributes to climate change. Previous studies also show existing relations with cardiovascular and respiratory diseases [4,5] and also classify this pollutant as carcinogenic [6]. Moreover, PM's black-carbon content boosts global warming whereas other elements such as, e.g. organic carbon, may have a cooling effect [7].

So far, most of the scientific publications in the disc brake aerosol research community have focused on emissions characterization; that in order to better assess how particles can interact with human beings and the environment. Hence, a wide variety of studies, performed at different test scales, is available: real scale (field tests) [8,9], system scale (dynamic bench tests) [10–12] and model scale (pin-on-disc tribometers) [13–15], among which promising correlations have also been found [16,17]. These scientific studies provide a qualitative description of particle emission in terms of size distribution, emission factors, chemical composition and particle morphology. However, they do not explain how the brake system parameters affect the generation of PM. Nevertheless, some interesting observations are provided. Kukutschová et al. [10] noticed an increase in particle number concentration in the ultrafine fraction when the rotor temperature exceeded 300 °C. Garg et al. [11] also noticed a mass reduction in the airborne fraction and an increase in particle number for temperatures close to 400 °C. Similarly, Wahlström et al. [18] found that the ultrafine number concentration in a pin-on-disc tribometer set-up increases by several magnitude orders for high load tests, i.e. the one with the highest disc temperature.

Few studies have tried to further investigate the causes of origin of particulate matter. Eriksson et al. have introduced the contact plateau models [19]. These plateaus were also observed by Österle et al. [20], while investigating tribofilm generation. Nevertheless, these studies focus on a mesoscopic scale to explain wear and friction mechanisms.

In order to include particles emissions in brake system design and simulation routines [21], a clear and complete understanding of their causes of origin, on a macroscopic scale, is still missing.

The aim of this study is to investigate how airborne PM emissions are influenced by typical car brake system parameters and map their relations. In particular, the following will be investigated: speed (v), contact pressure (p) and braking power (P). Temperature (T) will also be analysed as a significant response parameter, resulting from the developed braking power and the system cooling conditions. Speed and pressure can be classified as control parameters since they are governed by the driver; braking power is a derivative parameter since it depends on the control parameters and the coefficient of friction.

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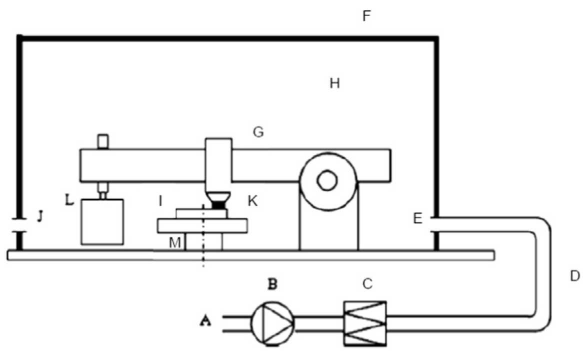

Fig. 1. Pin-on-disc tribometer scheme [22]. (A) Room air; (B) Fan; (C) HEPA Filter; (D) Flexible tube; (E) Clean air inlet; (F) closed box; (G) Pin-on-disc machine; (H) sampled air volume; (I) Rotating disc sample; (J) Air outlet/sampling point; (K) pin sample; (L) Dead weight; (M) rotating base.

2. Method

2.1. Experimental set-up

All tests were performed on a model-scale, making use of a pin-on-disc tribometer with a horizontal rotating disc and a dead weight loaded pin, enclosed in a sealed chamber. This system, previously described by Olofsson et al. [22], has specifically been designed for airborne particles measurements. While such set-up substantially differ from a real vehicle set-up for, e.g., the contact orientation and the lack of dynamics, which should be considered for future studies, is nowadays difficult to measure emissions on-road due to the relevant number of emission sources [23]. In addition the need to have a simplified model of the brake contact, where a steady state can be reached, and parameters could be easily modified led to the usage of a pin on disc tribometer. Its scheme is provided in Fig. 1. Ambient air (A), with a mean relative humidity of 24 ± 1% and mean temperature of 20.5 ± 1.2 °C, enters the system. The air is forced by a pump (B), set to a flow-rate of 7.7 m^3/h, through an HEPA filter (C). The latter removes particles with a collection efficiency of 99.95%, at the Maximum Penetrating Particle Size (Class H13 according to standard EN 1822). The now clean air enters the sealed test chamber (F) through the inlet (E). Here, the air-flow is continuously controlled by a hot-wire anemometer. The pin-on-disc tribometer lies inside the chamber. The approximate volumes are 0.135 m^3 and 0.035 m^3 respectively, giving an air-volume exchange rate of about 77 exchanges/h.

A thermal insulating ROBURIT® back-plate is fixed on the rotating base (M) and the disc sample (I) is screwed on top of that. The latter can rotate up to 3000 rpm thanks to a synchronous servo motor. Conversely, the pin (K) is mounted in a stationary pin-holder; this is fixed on an arm (G) at the end of which a dead weight (L) is positioned. The ratio between the arm hinge, the pin position, and the dead-weight is fixed, intensifying the normal force by 2.1 times (e.g. a normal force of 30 N at the tip of the arm provides 63 N on the pin). Differently, the tangential force is measured by a beam load cell with a nominal load of 100 N and a nominal sensitivity of 2 mV/V.

When the system is loaded and the disc is rotating, the generated airborne fraction is well mixed to the clean air volume (H). This is because of the complicated internal geometries. The air flux finally passes through the chamber outlet (J) where it is sampled.

At the outlet, particle emissions were measured using a DEKATI® ELPI+™, an Electrical Low Pressure Impactor; this both counts and collects particles on aluminium filters, in a size range of 0.006–10 µm, divided into 14 different stages. The sample flow-rate is imposed at 10 L/min. The sampling rate was set at 1 Hz, a good enough frequency not to hide interesting phenomena, as shown from another study performed on a system-scale [24]. Even though pin-on-disc tests provide mainly stationary conditions, particle emissions can show dynamic behaviour depending on the system temperature; the latter was therefore measured using K-type thermocouples. Only the disc temperature was acquired, using a slippery contact. The sampling rate was set at 2 Hz.

Table 1
Pin/pads chemical composition [wt%] obtained by XRF analysis.

Mg	Si	Al	S	Ca	Fe	Cu	Zn	Cr	Zr	Sn	Ba	C
11.1	6.3	9.8	5.6	5.2	7.6	5.8	13.4	3.5	0.1	9.3	–	22.3

Table 2
Disc/rotor chemical composition [wt%] obtained by optical emission spectrometry.

C	Si	Mn	P	S	Cu	Cr	Fe
3.40	1.70	0.57	0.03	0.26	0.24	0.20	93.6

2.2. Materials

Pin samples with a 10 mm diameter were machined from a real low-steel brake pad the XRF composition of which is shown in Table 1. The same pad material has previously been investigated by Alemani et al. [25] and code named M1. Equally, disc samples with a 63 mm diameter and 6 mm thick, were machined from a real disc braking surface, the chemical composition of which is shown in Table 2. Both specimens were taken from a typical European car brake system as described by Holmberg et al. [26]. This consists of a four piston monolithic calliper, two low-steel brake pads with a surface area of 77 cm^2 and a ventilated cast iron disc. The vehicle specifications can be found in [27]. Each pin and disc sample was drilled to allow temperature measurements 3 mm below each contact surface. The disc centre to pin-centre distance was set to 25 mm, also corresponding to the disc temperature measurement point.

2.3. Design of experiment

Two tests for each pressure-velocity combination, as provided in Table 3 and shown in Fig. 2, were performed. The run order was randomized to reduce systematic errors. The selected levels were chosen considering urban driving conditions. For the chosen vehicles, fluid pressures were in the range 18–45 bar, while vehicle speeds were between 5 km/h and 62 km/h. The same pressure levels were used by Alemani et al. [25]. In addition, the present study expands the investigation to different speed levels.

Once the pin-on-disc tribometer was completely set, and the chamber cleaned and sealed, the pump was turned on. This was to flush

Table 3
Summary of the testing conditions for the full test plan. Conditions used for ANOVA are marked by a + or -, indicating high or low levels respectively. Subscript indexes 1 and 2 indicate to which performed ANOVA they belong (1. pressure-velocity, 2. pressure-frictional power).

Test ID	Sliding velocity [m/s]	Nominal contact pressure [MPa]	Sliding distance [m]	Test time [s]	Frictional power [W]
1	0.66	1.67	14148	21,600	43.0
2	1.31 ($-_1$)	0.55 ($-_1$)	14148	10,800	28.7
3	1.31 ($-_1$)	1.11 ($+_{1,2}$)	14148	10,800	57.3 ($_2$)
4	1.31	1.67	14148	10,800	86.0
5	1.97 ($+_1$)	1.11 ($+_{1,2}$)	14148	7200	86.0 ($+_2$)
6	1.97 ($+_1$)	0.55 ($-_1$)	14148	7200	43.4
7	2.62	0.55($-_2$)	14148	5400	57.8 ($-_2$)
8	3.92	0.55 ($-_2$)	14148	3598	86.7 ($+_2$)
9	7.86	0.13	14148	1800	43.0

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